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Z AXIS TRACKER

The Field of the Invention

The present invention relates to a method and apparatus for tracking the position of an object surface. The invention is especially useful in the accurate placement of a laser's focal point during surgical laser procedures, of application - for example - in operations involving intrastromal ablation of the cornea, in the refractive correction of the eye, and in phacoemulsifaction procedures, where the lens of the eye is liquefied for easy removal. The invention will be described in terms of these applications, but is not restricted thereto. For example, it will be understood that the present invention may be applied to other medical laser procedures in which depth tracking is required.

Background Art

Intrastromal Photorefractive Keratectomy (intrastromal PRK or IPRK), also known as intrastromal ablation, involves focusing a short pulsed (< 50 ns), near infrared or visible laser to a point inside the cornea. Unlike the excimer laser, short-pulsed visible and near infra-red lasers are not absorbed highly enough by biological tissue to cause photodissociation or "ablation". Instead, the mechanism of tissue removal involves plasma-mediated photodisruption, with the development of cavitation bubbles and shock waves beneath the laser's target zone. If a sufficient energy density is reached inside the tissue, optical breakdown occurs and a small volume of tissue at the laser's focal point is vaporised.

A number of studies have been conducted into the feasibility of using intrastromal PRK for correcting refractive errors of the eye (see for example Habib et al, "Myopic Intrastromal Photorefractive Keratectomy with the Neodymium - Yttrium Lithium Fluoride Picosecond Laser in the Cat Cornea", Archives of Ophthalmology (1995) 113:499-505 or Hoi et al, "Picosecond Laser in situ Keratomileusis with a 1053-nm Nd:YLF Laser", Journal of Refractive Surgery

(1996) 12:721-728. Intrastromal PRK leaves the corneal epithelium and endothelium intact, preventing potential complications such as infection, and facilitating wound healing. Tissue effects appear confined to the cornea's stromal area, with small thermal damage zones and the appearance of normal collagenous stroma by six months post-surgery, with the use of the ultrashort Nd:YLF laser in cat cornea (Habib, Speaker, Kaiser & Juhasz (1995)). Intrastromal PRK may therefore have the ability to provide a more predictable refractive outcome, with the prospect of fewer complications than may occur with conventional techniques. US Patent 5,112,328 describes a method and apparatus for applications involving intrastromal corneal ablation.

It has been suggested that the intrastromal technique can be used to remove an appropriate volume of tissue, to effect refractive correction in a similar fashion to those achieved in Laser-in-situ-Keratomileusis (LASIK) procedures, without the necessity of creating a flap, or to cut the flap during LASIK operations. The current microkeratomes used in refractive surgery such as LASIK are mechanical devices that have significant potential to malfunction, sometimes causing serious damage to a patient's eye. Using intrastromal ablation to create the flap in LASIK may be much easier than trying to use intrastromal ablation to effect a refractive change. The intrastromal flap has the potential to make LASIK a safer and simpler procedure to perform, without having to rely on the use of mechanical devices.

Although there may be significant advantages in using intrastromal ablation for procedures such as refractive laser surgery, the practical difficulties of aiming each laser pulse onto the correct location within the cornea has meant that IPRK is not yet routinely performed. In living eyes, the need to deposit each laser pulse in the correct spot places stringent requirements on tracking the eye not only in the horizontal and vertical directions but also in a longitudinal direction away from or towards the laser source (known as and referred to below as the "Z" direction). Techniques with the appropriate resolution to accurately track eyes undergoing

surgery in the Z direction have not yet been fully developed.

US Patent 5,162,641 describes an eye tracking system, based on the principle of confocal microscopy, for measuring depth movement in eye tissue during laser surgery. This invention uses an illuminating light, a pinhole and a detector, located behind the optics of a laser system, to monitor the depth of a reflection along the optical axis. The system is arranged so that the maximum intensity of light reflected from the eye is directed onto the detector unit. The eye tracker focuses on an anterior reflective surface, such as the corneal tear layer, or a similar reference point with a known relationship to the target of the laser beam, and not necessarily on the target itself. When the tissue in the laser beam's focus moves, signals from the photodetector/pinhole arrangement decrease. These signal changes are then used to drive the optics of the laser system to compensate for the tissue movement, thereby moving the objective lens and repositioning the laser's focus. Focus monitoring may also be achieved by dithering the pinhole/photodetector unit to determine the direction in which signal increase occurs.

US Patent 5,336,215 (Intelligent Surgical Lasers) teaches an eye stabilising mechanism for use with a computer controlled ophthalmic laser system, specifically for use in intrastromal PRK or phacoemulsifaction procedures. This laser delivery system employs suction to immobilise the eye. A contact lens with limbal suction eliminates the need for a non-contact eye tracking device. A moveable objective lens controls the position of the laser's focal point through the various tissues of the eye in the X and Y or Z directions. Nevertheless, devices such as the one described above are not ideal for use in intrastromal ablation procedures: they have the potential to raise intra-ocular pressure, deform the shape of the eyeball and cause discomfort to the patient. The contact lens must also be made to conform to the individual patient's corneal topography. In addition, the reliance on suction to hold a device on the eye is one of the main reasons why current microkeratomes cause complications.

A general technique that can be used to measure surface topography is optical coherence tomography (OCT), also known as short coherence length interferometry. OCT usually involves splitting light from a low coherence light source (such as a superluminescent diode) and transmitting part of that light to the object of interest (for example, a cornea) and the rest to a reference surface (for example, a flat mirror). The light is then combined again at a detector. Only when the distance to the reference surface matches the distance to the object of interest do the light beams from the two paths interfere with each other to form intensity variations at the detector. The reference surface is usually scanned backwards and forwards so the intensity variations at the detector form a signal that is easily detected using electronic filters.

US Patent 5,465,147 describes a general OCT-based system and technique for acquiring a digital image of a region of an object using a CCD array as a detector to image the interference pattern. In this case, a reference scatterer is employed rather than a flat mirror and this scatterer is moved towards and away from the beamsplitter in a predetermined pattern to generate a detectable variable interference signal. It is also suggested that the scatterer be vibrated or dithered back and forth about a single depth point at a predetermined frequency in order to provide a series of two dimensional images in the transverse direction at that single depth point.

US Patent 5,644,642 teaches a gaze tracking device that employs OCT. This device uses measured height information of the features of the eye to improve the accuracy of tracking the eye in the X and Y directions. An optical fibre is used to transmit radiation which has a short temporal coherence length and is substantially spatially coherent, onto a scanning reference mechanism, which causes a focal spot of radiation to scan the plane of the pupil transversely across the pupil/iris boundary. A raster pattern or a coarse scan pattern featuring a grid of points is employed and information is collected at each point on the grid. Radiation reflected from the eye interferes which that coming from the reference

path, which has a known path length that may be varied intermittently. Output from the OCT device is then generated when the path length of the reflected radiation is equal to the reference path length. An identifiable signal is produced when the scan crosses the pupil/iris border, enabling the determination of depth information. A computer examines the position at which a change in depth exceeds a predetermined amount. Spatial coordinates are then used in conjunction with geometric equations to determine the pupil border and pupil centre.

Other ophthalmologic applications of OCT are noted in US patent 5491524, including the imaging of intraocular structures for determining a variety of measurements of the cornea, iris, crystalline lens and anterior chamber. The patent proposes an OCT corneal mapping apparatus that utilises a rotating helical reference mirror to generate a periodic variation of the detected interference signal. The height of the helical surface is set so that the depth scan provided by the optical path length variation of the reference arm of the interferometer setup is of the order of the corneal thickness, thereby reducing the scan volume and the data acquisition time. In a particular embodiment, a signal peak is detected in order to determine the depth of a particular corneal structure and successive such peaks are utilised to track the reference path retroreflector with the curve and shape of the cornea.

OCT thus provides an inexpensive, non-contact and non-invasive method of determining depth points within the eye. However, OCT apparatus of the prior art typically scan a reference surface around the full range of possible signals from above and below the corneal surface to the interior of the eye, as well as scanning in X, Y directions, which is not highly effective as a tracking technique. Moreover, OCT has not been proposed as a mechanism for accurate tracking during eye surgical procedures, probably because it would be viewed as too slow for this application.

It is therefore an object of the present invention to provide an improved

tracking method and apparatus that can track the movement of an object in the axial or Z direction and is preferably useful for this purpose in eye surgical procedures.

Summary of the Invention

The invention generally provides a method for tracking the position of an object surface, including generating an interference signal between light beams of short temporal coherence length respectively comprising a primary beam reflected or scattered from the object surface and a reference beam. A reference surface in the path of the reference beam is scanned about a position at which the interference signal is generated, which position is thereby indicative of the position of the object surface. In one aspect of the invention, the position of the reference surface is controlled to maintain a predetermined point in the range of the scanning at the indicative position. In another aspect, the interference signal is modulated with a characteristic predetermined repetitive variation.

The invention also provides apparatus for tracking the position of an object surface, including interferometer means for generating an interference signal between light beams of short temporal coherence length respectively comprising a primary beam reflected or scattered from the object and a reference beam. A reference surface is disposed in the path of the reference beam, and the apparatus further includes means for scanning the reference surface about a position at which the interference signal is generated, which position is thereby indicative of the position of the object surface. In one aspect, there is means for controlling the position of the reference surface to maintain a predetermined point in the range of the scanning at the indicative position.

In the other aspect, there is means to modulate the interference signal with a characteristic predetermined repetitive variation.

The reference surface preferably comprises reflection or scattering means.

Advantageously, the modulation is effected by additionally dithering the position of the reference surface.

Preferably, the control of the position of the reference surface is effected by dithering the reference surface about a location at which a peak interference signal is detected, and maintaining said predetermined point at the indicative position in response to the peak interference signal.

In an advantageous application the object is the cornea or iris of an eye.

The invention also provides a method of performing a surgical procedure at a sequence of points in tissue, wherein the correct location of the points is maintained by tracking the position of a related object surface according to the above described method. The surgical procedure may be a surgical laser procedure in which a laser beam is focused successively at the points in the tissue. The surgical procedure may comprise one or more of intrastromal photorefractive keratectomy, Laser-in-situ-Keratomileusis procedures or laser optical breakdown in phacoemulsifaction.

Preferably said ophthalmic laser surgery includes IPRK, cutting the flap in LASIK procedures, or phacoemulsifaction procedures.

Preferably said ophthalmic laser surgery includes optical breakdown caused by a short laser pulse within the tissue of the eye.

Brief Description of the Drawing

The invention will be further described by way of example only, with reference to the accompanying drawing, which is a schematic representation of OCT Z-axis eye tracking apparatus according to a preferred embodiment of the present invention, arranged for controlling the targeting of a laser beam being employed for performing a surgical procedure in the subject eye.

Description of Preferred Embodiments

In the illustrated OCT tracking apparatus, a beam of light 2, of short temporal coherence and produced by light source 4, is directed through beam-splitter 6. Light source 4 is suitably a superluminescent diode, producing a beam of visible or near infrared light. Beamsplitter 6 splits the beam into a reflected reference beam 8 and a transmitted primary beam 10. The primary beam 10 is directed onto an appropriate surface 12 of the eye to be treated, eg the front surface of the cornea, while the reference beam 8 is directed onto a reflective reference surface in the form of a flat mirror 14. Mirror 14 is scanned backwards and forwards in the direction of the reference beam 8 by means of scanning mechanism 15 which has a primary scanner 18 and a secondary dither scanner 16.

Light reflected from the mirror 14 interferes with reflected light from the corneal surface 12 and produces a characteristic interference signal detectable at and by photo-detector 20, as reference mirror 14 is oscillated by primary scanner 18.

The position of mirror 14 is scanned or oscillated to vary the path length of reference beam 8: when the total path lengths of the primary and reference beams are equal, the output signal from detector 20 (and transmitted to filter 22) reaches a maximum intensity. Thus, the intensity of the electronic signal sent to filter 22 is dependent on the position of the reflecting corneal surface 12 and therefore on the depth of the point of interest within the cornea at which a treatment laser beam 30 is to be focused for effecting intrastromal PRK. The detected signal may be analysed with respect to the position of mirror 14 to determine the signal peak that coincides with the position of the surface 12.

Mirror 14 is not necessarily an optical surface, or of optical quality, and is advantageously such that the reflected signals at beamsplitter 6 are of a similar order of magnitude. For example, a typical detected magnitude for the return

signal for a cornea might be around 4% of the incident signal, and this should preferably be matched in the interfering reflected reference signal.

For more efficient and accurate tracking, secondary dither scanner 15 is provided to dither mirror 14 about a position previously determined with scanner 18 that corresponds to the surface 12, and the detected peak interference signal is used to drive an offset to the position of the scanner 16 by scanner 18 to keep the reflecting surface of mirror 14 in the middle of the dithered range. The dither scanner 16 introduces a characteristic predetermined repetitive variation in the detected interference signal that can be filtered for efficient tracking. The presence of this modulation of the interference signal optimises the speed and accuracy of the tracking by allowing extraction of the surface position with less problems with noise. For example, phase sensitive detection might be advantageously employed.

The nature of scanners 14, 126 is not critical to the invention, and a suitable choice is readily made by those skilled in the art from a wide variety of options. One approach of interest for either or both scanners is a spinning cam, in which the reference surface is a cylindrical surface oscillated in the optical path by an eccentric rotating cam driven by an adjacent motor.

A controller 32 manages the tracking apparatus, interpreting the filtered detector signal, detecting the peak interference signal, and controlling both of the scanners 16, 18, and is linked to a surgical laser system 35 that generates treatment beam 30 so that the beam 30 may be targeted to successive points inside the cornea in response to the tracking of the corneal surface. The form and structure of controller 32 and of its circuits and firmware will be readily apparent to those skilled in the art of tracking and control instrumentation.

By means of suitable optics, beam 30 is typically delivered to the eye on a common optical axis with primary tracking beam 10: it will of course be understood that the configuration of optical components may be very different from that

illustrated, which is intended only as a simplified optical diagram for the purpose of explaining the concepts of the invention.

The illustrated configuration enables the precise tracking of surfaces within the eye, in real time and high resolution. The apparatus scans mirror 14 only about a position corresponding to the peak of the electronic signal from filter 22. The scanning range is equal to approximately ±1 to ±10 microns around the surface of the cornea. This configuration is therefore capable of giving a very sensitive depth measurement in the Z direction (towards the eye) with a fast response time. The preferred use of the second dithered scanner contributes to the fast response and therefore contributes to overcoming the traditional expectation, noted earlier, that OCT is too slow for the present application. During surgical procedures, a controller interprets the signals and send instructions to a surgical laser system to adjust the focal point of the laser according to movements of the patient's eye.

The OCT method and apparatus according to the present invention can provide information regarding the axial position of the cornea, enabling an ablative laser to be accurately focused on a spot within the cornea during operations such as intrastromal ablation or cutting the flap during LASIK. However, even with Z-axis tracking, eye movements in the X and Y directions can still affect the placement of the laser beam. A second preferred embodiment of the present invention (not illustrated), therefore includes gaze tracking apparatus capable of tracking transverse eye movements. Any suitable means of horizontal and vertical eye tracking may be employed to detect alterations in the coordinates of the centre of the pupil, which indicate that horizontal or vertical eye movements have occurred. Adjustments in the laser's focal point can therefore be made in any direction, according to movements of the patient's eye.

Optional infrared lights may be included to track eye gaze in the horizontal and vertical directions.